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LONGITUDINAL MODES IN A HIGH-GAIN LASER

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In lasers employing high-gain narrow-linewidth transitions the theory predicts major departures of the mode-splitting frequencies from their low-gain values as well as a new type of mode splitting. The first of these effects consisting of a reduction by a factor of 2.5 of the mode splitting in a xenon 3.51-μ laser is observed experimentally.

The xenon laser at 3.51 μ exhibits extremely high gain and a narrow Doppler linewidth. There are a number of interesting laser phenomena which are enhanced in high-gain lasers and the xenon laser is well-suited for their study. In this paper we investigate theoretically and experimentally the very strong dependence of the longitudinal mode frequencies on gain.

The basic features of mode pulling in low-gain lasers are well known.[1] In particular, it is found that modes near the center of the gain spectrum are pulled toward the gain center but repelled from each other if saturation is important. In typical low-gain lasers the mode spacing may be reduced by at most a fraction of a percent from its empty resonator value. The mode spacing in helium xenon, on the other hand, may, in principle, be reduced by more than an order of magnitude due to the amplifying medium. Moreover, near the wings of the gain line the modes may split and display an increase in frequency with decreasing mode order. In other words, the frequency of radiation propagating through a highly dispersive medium may increase with increasing wavelength.

The laser systems in which the mode-structure distortion is likely to be most important are the inhomogeneously broadened gas lasers. The combination of high-gain and narrow linewidth in the Doppler-broadened lasers makes dispersion effects especially significant. As our starting point we use a relation derived by Close[2] for the frequency-dependent index of refraction of a Doppler-broadened amplifying medium. If the homogeneous linewidth $\Delta\nu_n$ is negligible compared to the Doppler width $\Delta\nu_D$ and saturation is unimportant, this relation takes the form

$$n(\nu) = 1 + [cgF(x)/2\pi^{3/2}\nu], \tag{1}$$

where $F(x)$ is Dawson's integral given by

$$F(x) = e^{-x}\int_0^x e^{t^2}\,dt. \tag{2}$$

The frequency is measured by $x = [2(\nu - \nu_0)/\Delta\nu_D] \times (\log 2)^{1/2}$ and g is the small-signal incremental-intensity gain constant at line center. Equation (1) is valid so long as $\epsilon(1+sI)^{1/2} \ll 1$, where $\epsilon = \Delta\nu_n/\Delta\nu_0$ is the natural damping ratio, s is the saturation parameter, and I is the intensity.

The phase condition which must be satisfied by an oscillating mode is that the real round-trip phase delay at the oscillation frequency ν be an integral multiple, say m, of 2π, or

$$2\pi m = \oint [2\pi\nu n(\nu, z)/c]dz. \tag{3}$$

If the cavity length is L and the length of the active medium is l, then Eq. (3) becomes

$$mc/2L = \nu\{1 + (l/L)[\bar{n}(\nu) - 1]\}, \tag{4}$$

where $\bar{n}(\nu)$ is the spatially averaged index of refraction of the medium. In terms of the empty resonator mode frequencies $\nu_m = mc/2L$, Eq. (4) may be written

$$\nu_m = \nu\{1 + (l/L)[\bar{n}(\nu) - 1]\}. \tag{5}$$

This is the general result for the mode frequencies of a laser containing a dispersive amplifying medium.

Using Eq. (1), Eq. (5) becomes

$$\nu_m - \nu = \frac{l}{L}\frac{cgF(x)}{2\pi^{3/2}}$$

or

$$x_m - x = \beta F(x), \tag{6}$$

where we define the dispersion parameter β as

$$\beta = \frac{l}{L}\frac{cg(\log 2)^{1/2}}{\pi^{3/2}\Delta\nu_D}. \tag{7}$$

Equation (6) may be used to determine the oscillation frequencies of a laser in which the amplifying medium is predominantly Doppler-broadened.

For lines near gain center ($x \ll 1$) Dawson's integral simplifies to $F(x) \approx x$. With this approximation Eq. (6) may be solved with the result

$$x = x_m/(1+\beta). \tag{8}$$

The mode spacing is reduced from its empty resonator value $\Delta\nu_0 = c/2L$ according to

$$\Delta\nu = \Delta\nu_0/(1+\beta). \tag{9}$$

For example, in a typical helium-neon laser at 6328 Å the Doppler linewidth is about 1800 MHz and the gain may be $g = 0.1\ \text{m}^{-1}$. Then, from Eq. (7), the dispersion parameter is roughly $\beta = 0.2\times 10^{-2}$ so that mode pulling reduces the mode spacing by only about 0.2%. On the other hand, in a high-gain helium-xenon laser at 3.51 μ the Doppler linewidth is about 100 MHz and the gain[3] may be 400 dB/m or $g = 92$. In this case the dispersion parameter is $\beta \approx 40$ and the mode spacing is reduced by more than an order of magnitude from its empty resonator value. There is a corresponding improvement in the laser stability with respect to mirror displacement.

So far attention has been restricted to frequencies near gain center where dispersion is linear. However, in high-gain lasers oscillation may be obtained in the wings of a resonance line where the dispersion effects are strikingly different. Equation (6) may be written

$$F(x) = (x_m - x)/\beta. \tag{10}$$

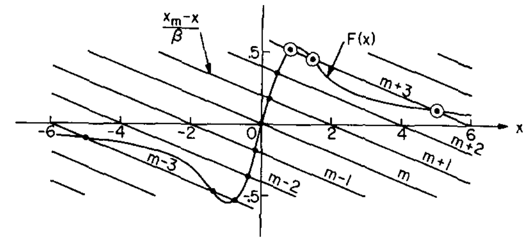

FIG. 1. Plot showing the graphical solution for the oscillation frequencies in a high-dispersion laser.

Perhaps the simplest way to see the qualitative implications of this equation is by a graphical solution. In Fig. 1 graphical solutions of Eq. (10) are shown for $\beta = 10$ and an empty resonator mode spacing of $\Delta x_m = 2$. The mode structure bears little resemblance to its empty cavity form. Near line center the spacing is reduced to $\Delta x \approx 0.2$. In the wings the modes split and occur at three different frequencies as indicated by the circled intersections in the figure. In other words *there may be three frequencies which all correspond to the same number of half-wavelengths between the mirrors.* Moreover, the modes occurring between approximately $x = 1$ and $x = 2.5$ are in reverse order with the higher-frequency modes having longer average wavelengths inside the resonator than lower-frequency modes.

All of the features of Fig. 1 should be observable in a helium-xenon laser. A necessary condition for mode splitting may be shown to be

$$\beta > 3.51. \tag{11}$$

This condition is readily met in xenon and helium xenon at 3.51 μ. In fact these are believed to be the only continuous lasers in which mode splitting could presently be observed.

The laser used in our experiments has a pure xenon dc discharge 5.5 mm in diameter and 1.1 m long. The cavity length was 1.36 m and the pressure was maintained at about 5 μ by using a liquid-nitrogen trap.[4] The beat frequency was measured by a Hg: Ge detector cooled to liquid-hydrogen temperature followed by a spectrum analyzer and a lock-in amplifier.

Figure 2 shows some typical beat-frequency data plotted versus the square root of the output power for a discharge current of 75 mA. The power is varied by changing the losses within the cavity. These results agree qualitatively with a more general theory including saturation effects. The power scale represents the lock-in amplifier meter reading, and the calibration was made with an Eppley

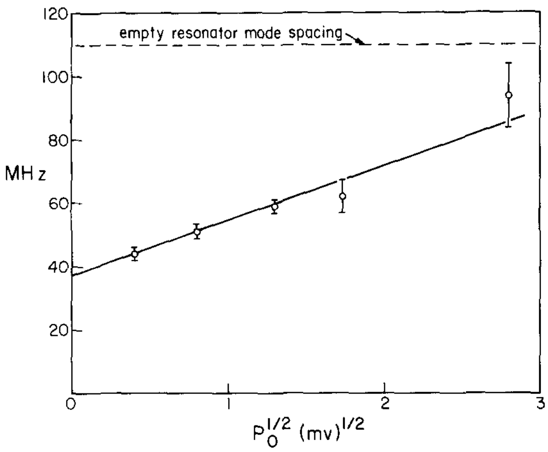

FIG. 2. Intermode frequency spacing of a xenon 3.51-μm laser versus the power output.

thermopile. Near threshold the mode spacing is reduced by about a factor of 2.5 from its empty resonator value. At higher powers, where saturation becomes important, the mode spacing approaches the empty resonator value.

For conditions under which saturation and spontaneous emission effects are unimportant it is found that the experimental value of β is proportional to the line center gain g as expected from Eq. (7). However, the proportionality constant is about half of what one would expect assuming a Doppler linewidth of 100 MHz. This discrepancy is resolved if we assume volume-effect isotope shifts of about 25 MHz per amu which could result from the p character of the lower laser level. Such shifts would lead to an effective broadening of the Doppler line. This interpretation is supported by an observed asymmetry in the power output as the laser is scanned through several longitudinal modes by translation of one cavity mirror. Preliminary investigations of these isotope shifts and of the hyperfine structure of the odd isotopes[5] suggest that the high gain of the 3.51-μ transition is due primarily to isotope 132 which constitutes only 27% of the natural abundance of xenon. Consequently a helium-xenon laser using pure xenon-132 might be capable of gains of the order of 1000 dB/m

For various reasons the laser system used in these experiments was not well-suited to investigation of the extreme mode pulling and mode splitting which should be observable in xenon and helium-xenon lasers. Experimental and theoretical studies of these and related high-gain effects including spectral narrowing are continuing.

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MOLYBDENUM FILMS AS PARTIAL DIFFUSION MASKS IN MOS PROCESSING

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Thin molybdenum films ~1000 Å deposited on thermal SO_2 grown on Si are observed to act as partial masks for B diffusion. B-doped glass is used as a diffusion source. Detection of the diffusion front is through measuring C-V curves for the MOS structure with molybdenum as the metal electrode. The above process is used to fabricate low threshold enhancement mode and depletion mode p-channel MOSFET's in one diffusion step.

It is the purpose of this letter to disclose a new method of producing low surface concentrations of B impurities in Si MOS structures by controlled diffusion of B through the Mo gate electrode film and underlying SiO_2 into the Si, without altering the qualities of the SiO_2 layer. This diffusion process lends itself to new fabrication methods for MOSFET's and integrated circuits.

The use of refractory metal films (Mo, W) as etch and/or diffusion masks for semiconductor processing has been reported.[1-3] For instance, self-registered Si MOSFET's have been formed using patterned refractory metal films as diffusion masks.[2,3] In turn, the high conductivity of these refractory metal films can yield integrated circuit interconnections with excellent high-frequency characteristics.[3,4]

The uninhibited diffusion of Zn through refractory metal contacts on GaAs has been reported[5]; however, the discovery that Mo is only a partial mask to B diffusion and that B can be diffused through Mo and SiO_2 in a refractory metal MOS structure in order to either eliminate the n-type Si surface normally present at the Si-SiO_2 interface or to produce lightly doped p-type surfaces is described below.

MOS-$C(V)$ curves are utilized to measure the resultant B surface concentration in the Si following each diffusion step. Measurement of capacitance versus voltage is made using a continuous plotting